University of Delaware
Center for Composite Materials
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2D DISTRIBUTED SENSING VIA TDR

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Relevance

Sensors are needed for processing QA/QC and for health monitoring:

- ✓ Flow front detection,
- ✓ Cure behavior,
- ✓ Defect detection,
- ✓ Process strain,
- ✓ Service related strain.

In the last decade various research has been conducted in this field developing flow, cure and strain monitoring sensor systems.

Advantages of TDR Sensors

Comparing with other sensor types (DC resistance, AC Dielectric, Optic fiber, Ultrasonic and other) TDR sensors have the following advantages:

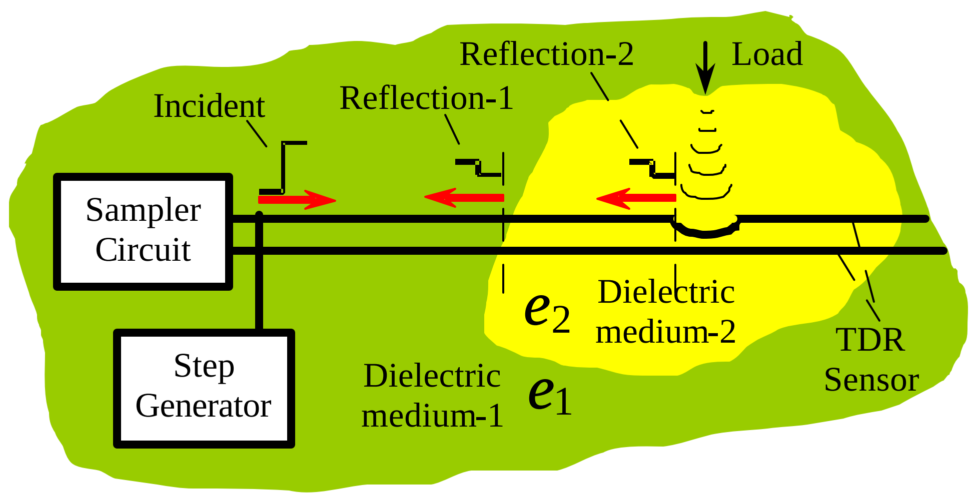
- ✓Low cost,
- ✓Tool-mounted and embedded configurations,
- ✓High accuracy (3mm),
- ✓**Multifunctional sensing**,
  - Resin flow behavior,
  - Cure,
  - In-service strain response,
- ✓**Distributed 2D sensing**.

TDR sensors completely fulfill the requirements for next generation sensors!

TDR Method for Sensing TL Discontinuities

Time domain reflectometry (TDR) is a method of sending high rise (35ps) voltage step-pulse into transmission line (TL), and detecting reflections returning from impedance discontinuities within the TL.

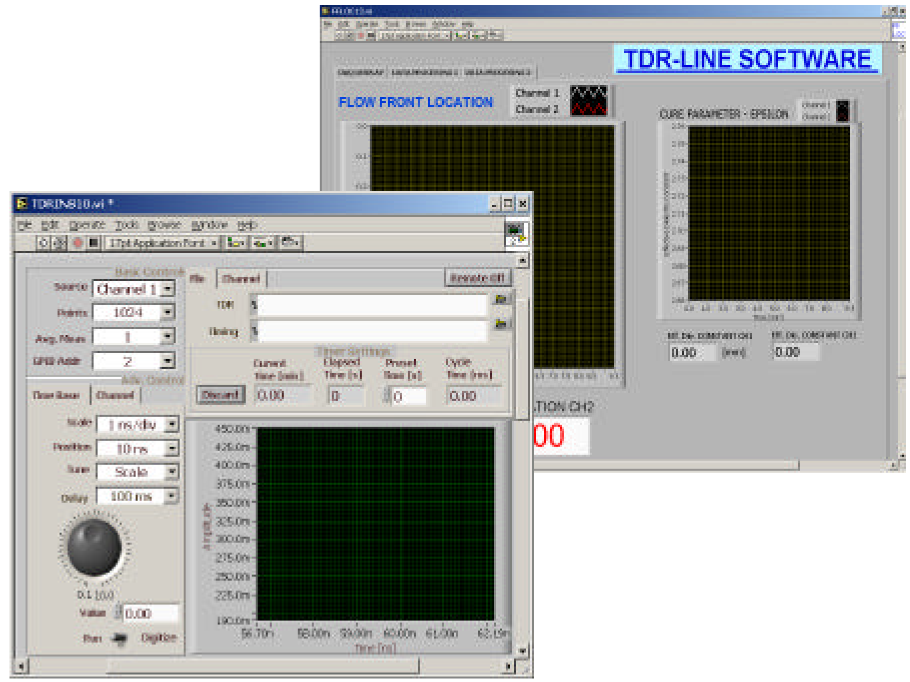
✓Any dielectric and/or geometrical discontinuities in the TL change the characteristic impedance, and introduces a voltage reflection at a particular time and magnitude.



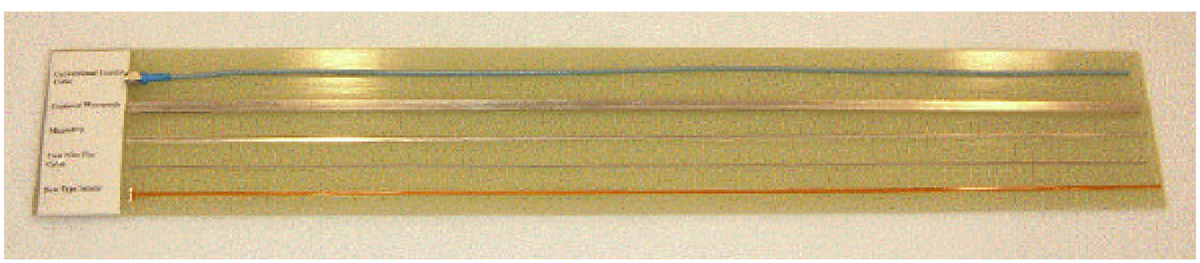
Schematic representation of operating principle of TDR Sensor for distributed and multifunctional sensing.

Hardware and Software

- ✓HP54750A (18GHz bandwidth) oscilloscope
- ✓GPIB interface.
- ✓ DAQ software written in LabVIEW.
- ✓Developed Multi-section TL-sensor modeling software.

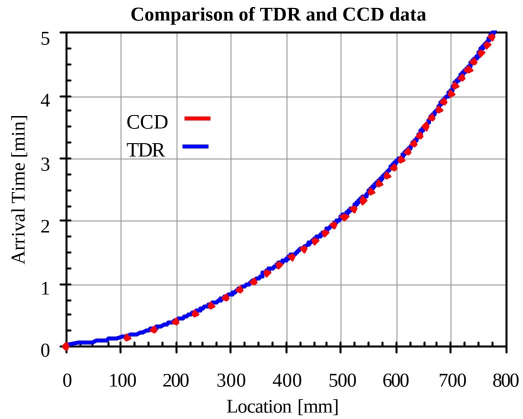


Various TDR sensors

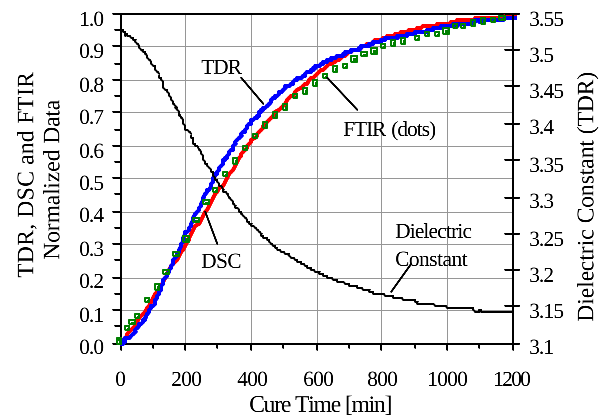


Previous Accomplishments

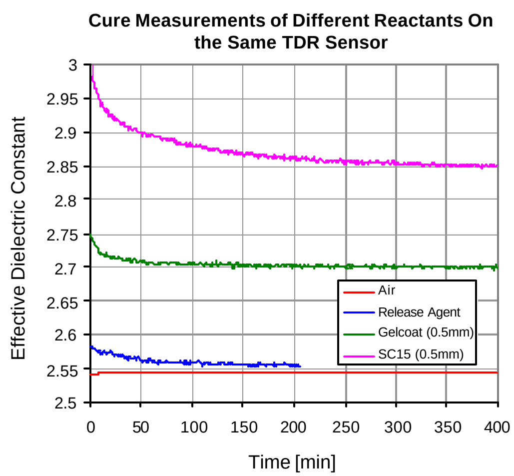
✓Accurate (3mm)1D flow sensing



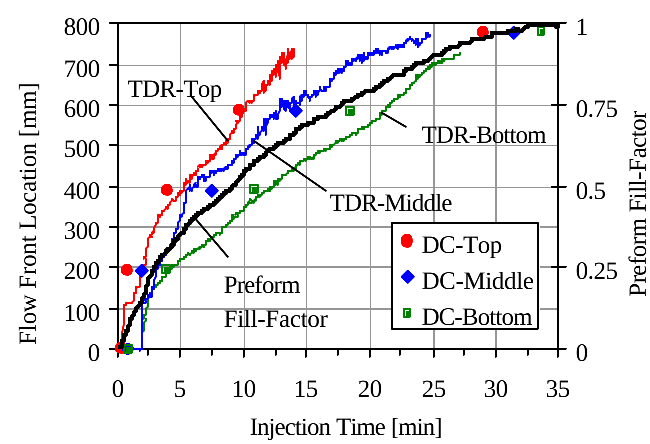
✓Accurate cure sensing of epoxies



✓Sensing through intermediate layers



✓Sensing of several flow fronts

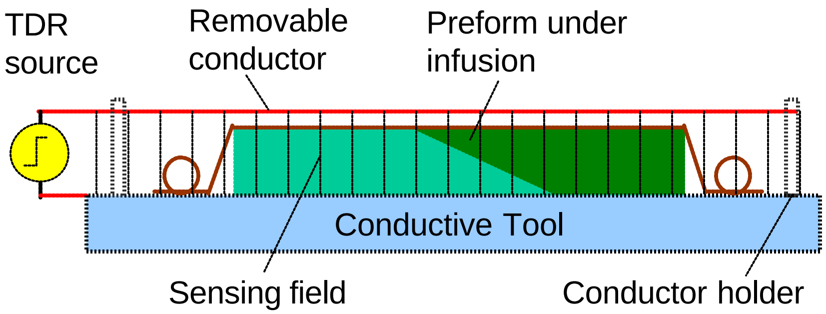


New Work

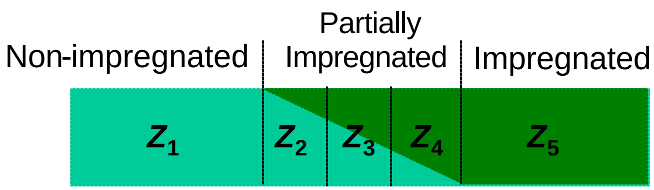
Developed multi-section TDR sensor model, which accounts for frequency dependant and multi-relaxation dielectric properties. This models will allow:

- ✓ **2D Flow sensing;**
- ✓ **Accurate sensing of multiple flow fronts;**
- ✓ **Cure characterization of various resins.**

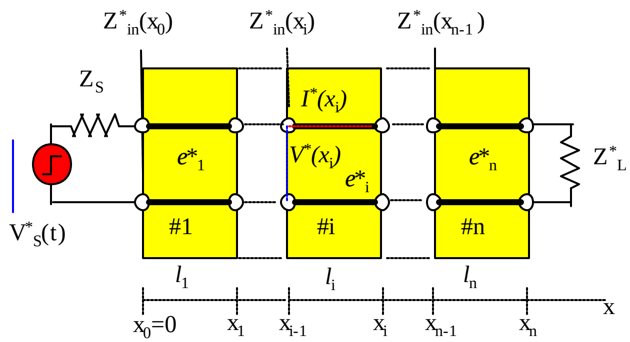
Vision: Non-contact 2D sensing



- ✓ VARTM setup constructed within TL can be sensed by its EM field: 2D flow, curing and process strain.



- ✓ 2D Flow reconstruction is using combined (effective) dielectric behavior of several materials.



- ✓ It affects the TDR response and can be modeled as a non-uniform TL with multiple uniform sections.

Model I

If

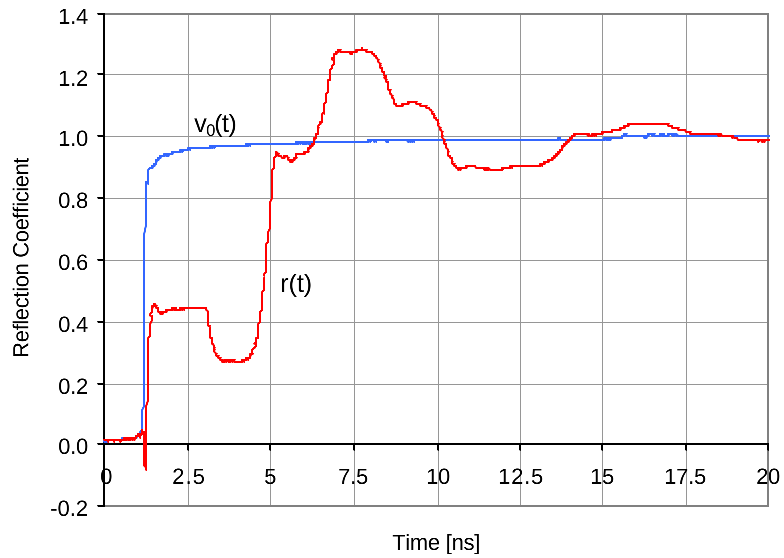
$r(t)$ is response function,

$v_0(t)$ input signal,

$s(t)$ and system function

then frequency dependent response can be obtained [Press et al.,1986]:

$$R(f) = V_0(f)S(f)$$



in which, $R(f), V_0(f)$ and $S(f)$ are FFTs of $r(t), v_0(t)$ and $s(t)$

f is frequency in Hz.

$v_0(t)$ can be obtained by measuring system response without the sensor or can be modeled:

$$v_0(t) = \frac{1 + erf\left[\frac{1}{t_r}(t - t_0)\right]}{2},$$

where, t is time, t_r rise time and t_0 signal position.

Model II

$S(f)$ can be described with so-called scatter function [Heimovaara, 1994]:

$$S_{11}^{k} = \frac{r_s^k(f) + S_{11}^{k-1}(f)\exp(-2gL)}{1 + r_s^k(f)S_{11}^{k-1}(f)\exp(-2gL)} \quad \text{with} \quad r_s^k = \frac{Z_{k-1}(f) - Z_k(f)}{Z_{k-1}(f) + Z_k(f)}$$

being the reflection coefficient between different sections k .

$Z_k(f)$ is frequency dependent impedance of TL section k and is calculated with:

$$Z_k(f) = \frac{Z_{0,k}}{\sqrt{e_k^*(f)}}$$

$Z_{0,k}$ is characteristic impedance of TL section k.

$e_k^*(f)$ is frequency dependent dielectric permittivity of TL section k , and can be described with Debeye relaxation function [Hasted, 1973]:

$$e_k^*(f) = e_{k\infty} + \frac{e_{ks} - e_{k\infty}}{1 + i\dfrac{f}{f_{k\,rel}}} - i\frac{s_{kDC}}{2p f e_0}$$

Where, s_{kDC} is the DC conductivity,

e_{k0} is the dielectric permittivity of free space

e_{ks} is the relative static permittivity

$e_{k\infty}$ is the relative high frequency permittivity and $f_{k\,rel}$ is the relaxation frequency.

Model III

The losses due to dielectric dielectric relaxation and direct current conductivity are given by:

$$g L_k = \frac{i2p\, f L_k \sqrt{e_k^*(f)}}{c}$$

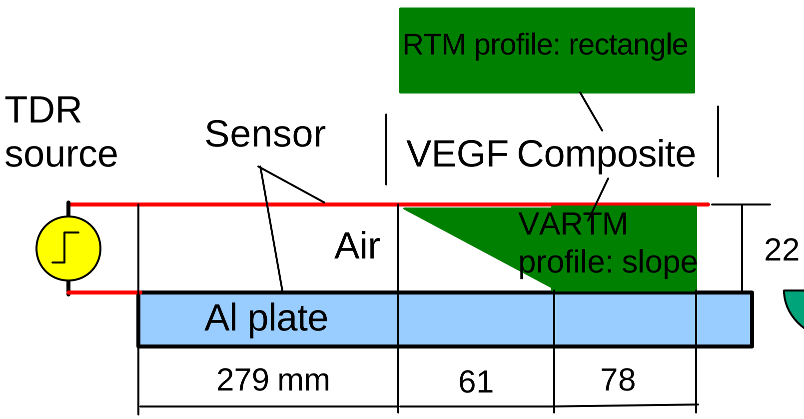
where, g_k is complex propagation constant,
L_k is TL section k length and
c is EM velocity in vacuum (300 mm/ns)

Calculation procedure:

1. All scatter functions $S_{11}^k(f)$ are calculated from the section n towards the source;
2. FFT of input signal $v_0(t)$ is calculated;
3. Inverse FFT of the product of $S_{11}^1(f)$ and $v_0(t)$ is calculated in order to obtain $r(t)$.

Experimental Setup

Experimental Setup



✓ Setup has replaceable vinyl ester glass fiber (VEGF) composite blocks to simulate resin profile

Goal:

✓ Prove 2D measurement concept;

✓ Establish measurement algorithms;

✓ Model comparison.

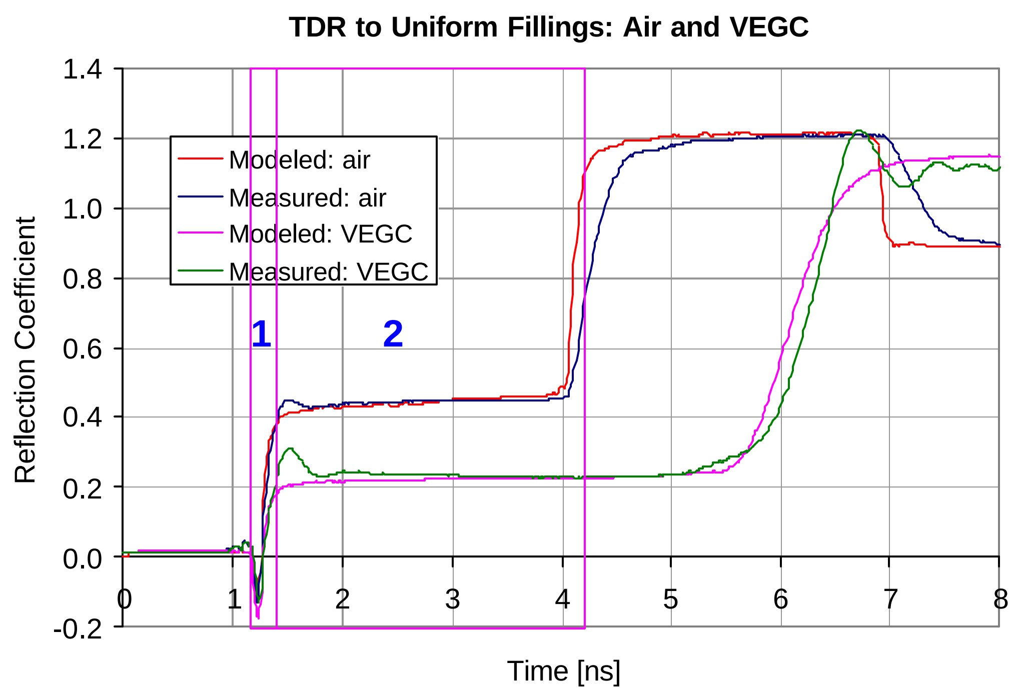
✓ Multi-section TL program have been developed based on scatter function and Debeye relaxation models.

VEGF Composite Dielectric Properties

✓ With this setup we determined Debeye parameters for VEGF Composite:

$e_S = 2.9$, $e_\infty = 2.0$,

$F_r = 2.5\ GHz$, $s_{st} = 0$



Configuration 1

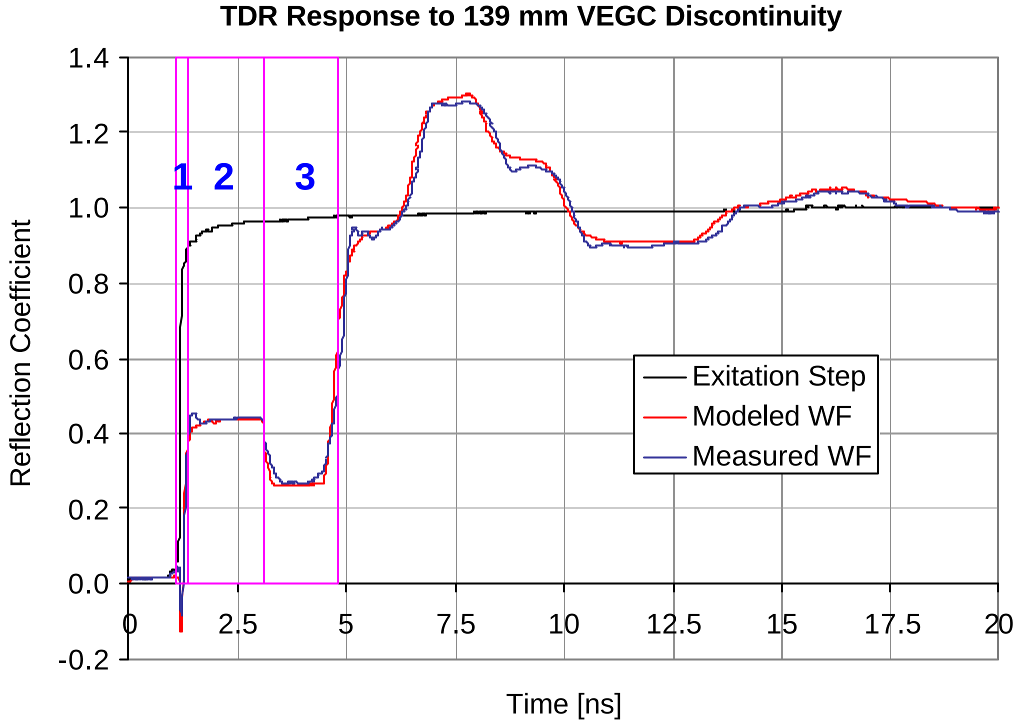
EM wave speed:

$V_e = 183.9$ mm/ns,

$V_a = 300.0$ mm/ns.

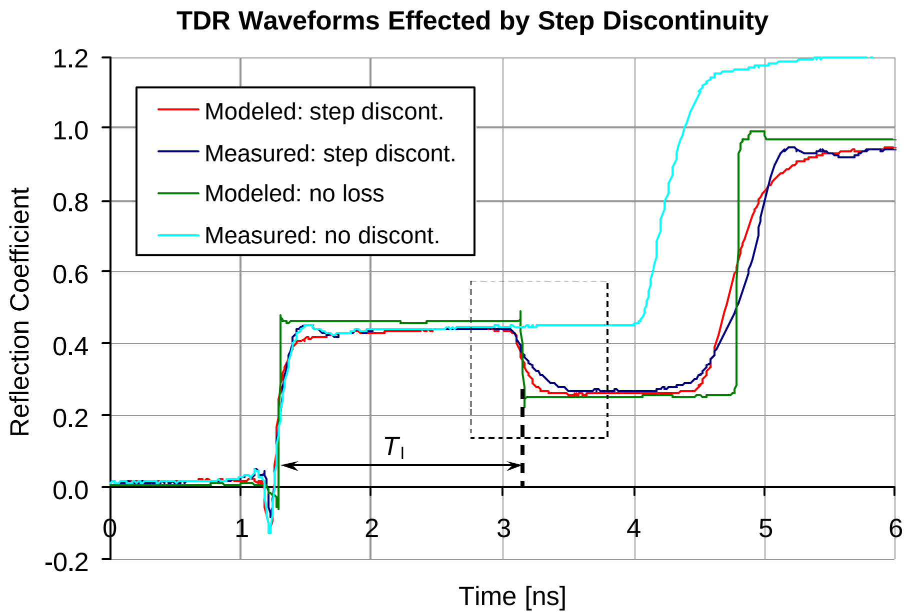
Model Validation "RTM Flow"

- ✓139 mm VEGF discontinuity shows clear change in TDR waveforms (WF).
- ✓Model fits the measured WF well showing attenuating successive reflections.
- ✓Minor mismatches are related with connector effects on WF scattering.



Configuration 2

TDR Waveform Distortions “RTM Flow”



WF “softening” is a function of:

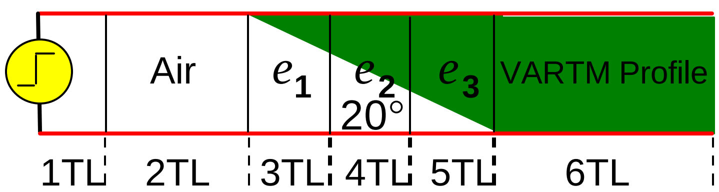
- ✦ excitation step rise time (47ps);
- ✦ dielectric loss;
- ✦ and relaxation frequency.

- ✦ Measured TDR WF have finite rise and fall times;
- ✦ Fall times and rise times introduces errors in calculation of locations.

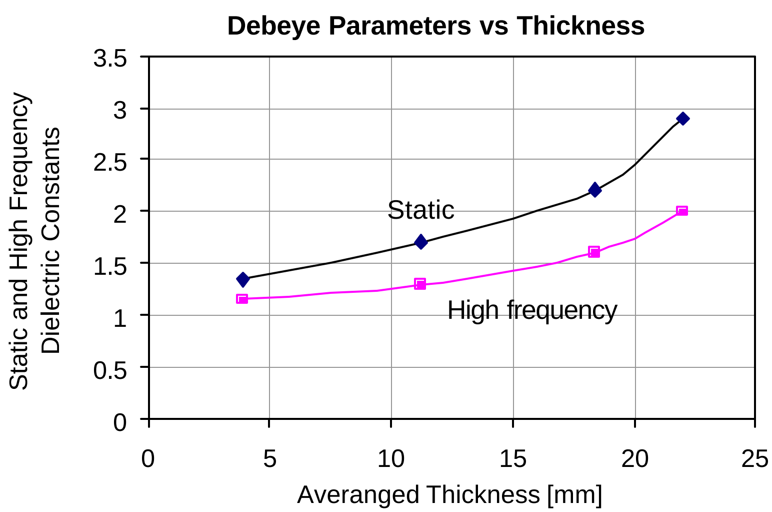
- ✦ Only the physical model of TL can generate zero loss and zero rise time WF’s.
- ✦ Superposition of such WF’s to the measured WF’s determines exact discontinuity location.

TDR Response to the "VARTM Profile"

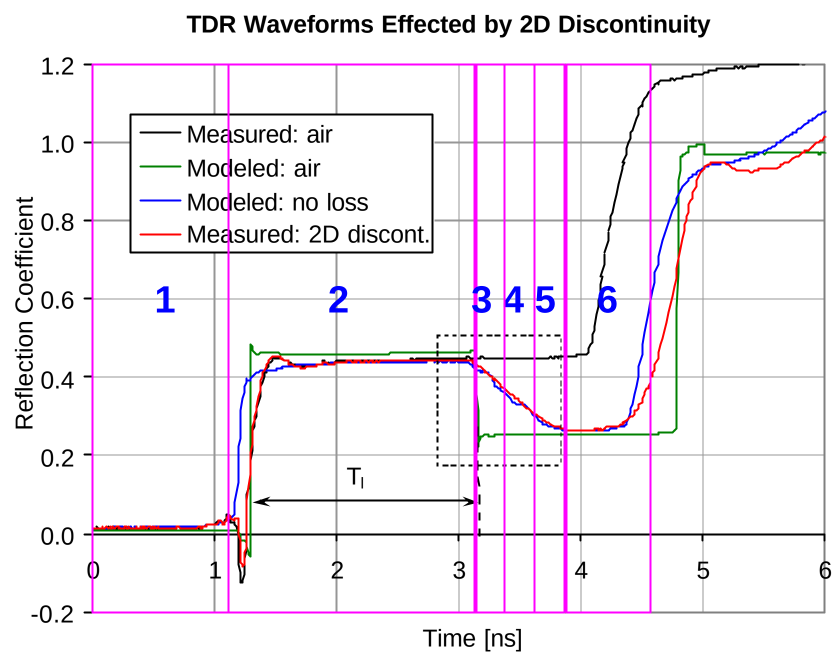
Configuration 3



- Dielectric parameters e_1, e_2, e_3 have been back calculated from the measured TDR-WF using a model.



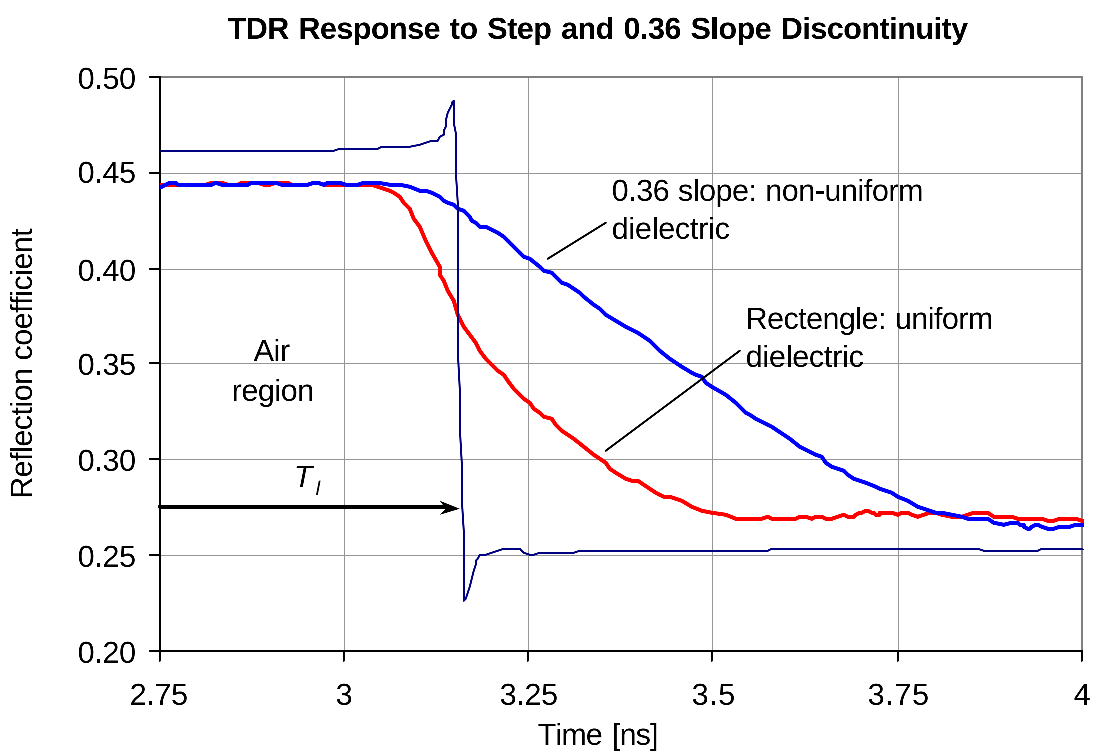
- The model with 6 TL sections was in good agreement with the experimental validations of the VEGF block which has 20° slope (0.36).
- Based on measurements only it is difficult to calculate slope location exactly because of high fall time.



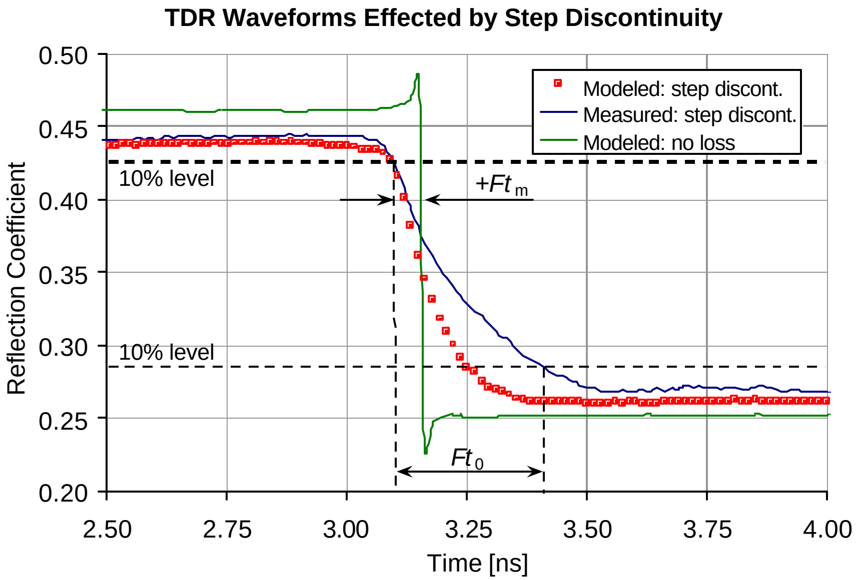
Discontinuity Comparison

- Different discontinuities result in changing rise time .
- Response to 0.36 slope is almost linear.
- It emulates real slope.
- Model based zero loss WF can be used to accurately determine the beginning of the discontinuity:

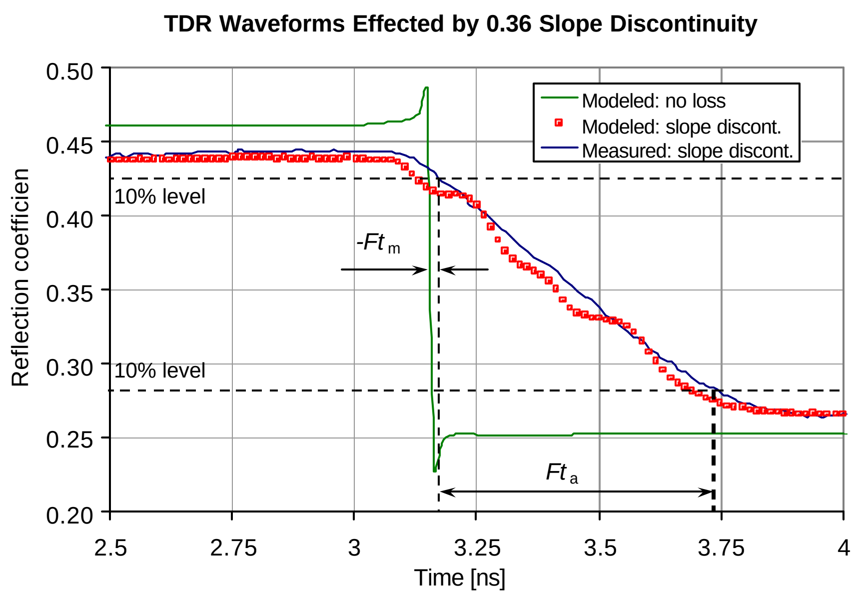
$$L_S = 300 \times T_l/2$$



2D Calculation Algorithm



1. Empirical or model-based values of ***Ft*$_m$** and e_1 as a function of ***Ft*$_a$**, material, geometry, and others must bee determined.
   Empirical method can be a very complicated and time consuming process!



2. Based on input parameters of actual WF, algorithm determines whether is step or slope like 2D discontinuity:

   If ***Ft*$_a$** » ***Ft*$_0$** Þ step

   If ***Ft*$_a$** > ***Ft*$_0$** Þ slope

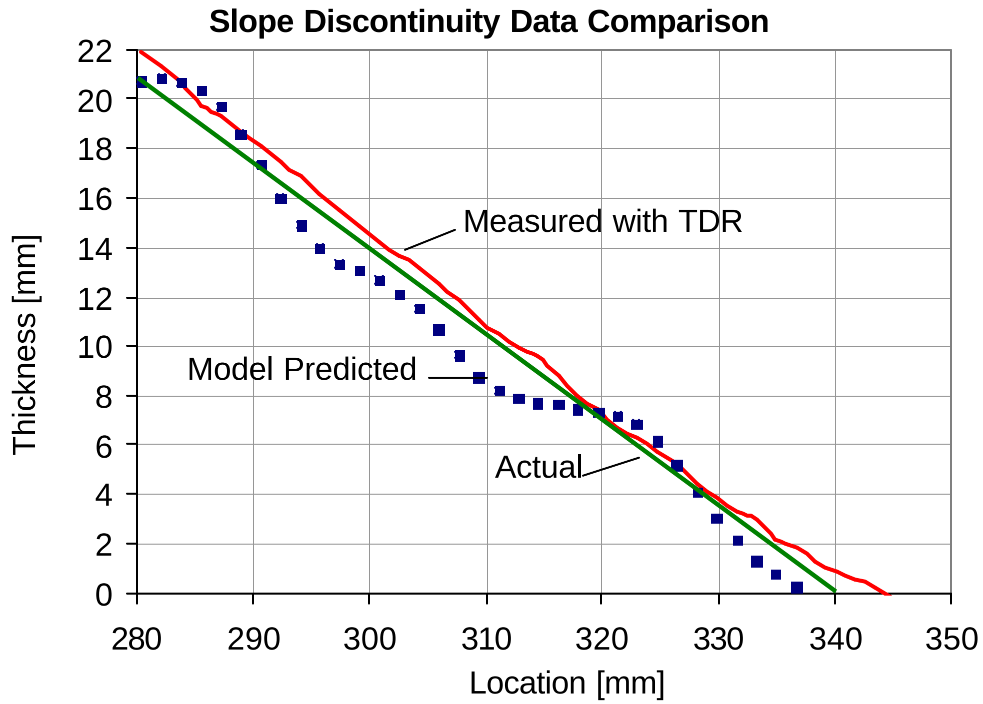
Algorithm and Validation

3. Based on value of ***Ft*** $_{m}$ 10% level data points will be shifted towards zero loss WF.

4. 10% level data points will be multiplied by averaged "slope" speed V_s = 231.3mm/ns and divided by two:

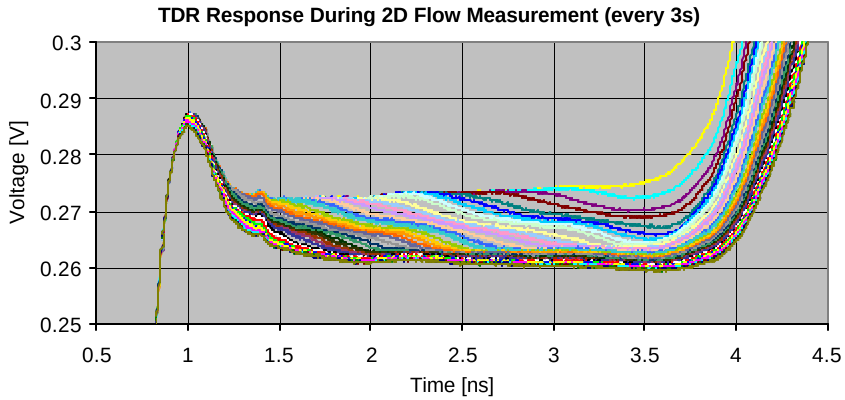
$$V_s = V_a \times \sqrt{\frac{1}{(e_1 + e_2 + e_3)/3}}$$

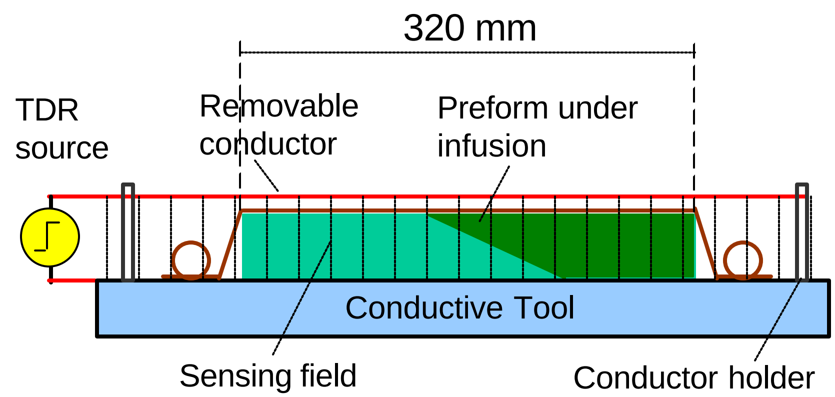
✓ Measured and model predicted slope fit actual slope very well showing accuracy of 3 mm.



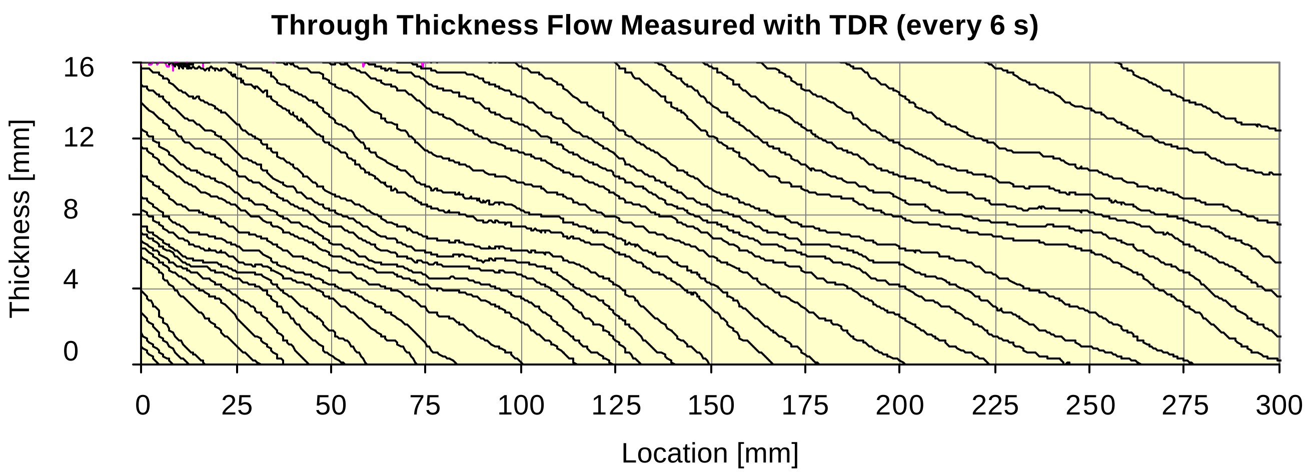
✓ Agreement of all three types of data proves 2D TDR measurement concept.

2D Flow Measurement During VARTM





- ✦ Good sensor response 14 mV;
- ✦ Sensor conductor was 3 mm above the preform;
- ✦ Results are similar to the validation results;
- ✦ In general 2D flow sensing concept based on TDR is validated.



Conclusions and Future Work

- TDR allows measurement of linear and through-thickness dielectric distribution:
- Modeled and measured waveforms emulate the shape of 2D discontinuity;
- Measurement accuracy of $\pm$ 3 mm can be achieved;
- Simple TDR algorithms can be applied for on-line intelligent composite processing.

- Integrated tool embedded TDR sensor in VEGF mold

- Future Work:
  - Further development of 2D sensing capability;
  - Development of TDR sensors for conductive fiber composites;
  - Investigate cure sensing of different resin systems.